Sedimentary Processes and Potential Geologic Hazards

on the Sea Floor of Northern Bering Sea

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ABSTRACT

A dynamic environment of strong bottom currents, storm waves, and gas-charged sediment on the shallow sea floor of northern Bering Sea creates several potential geologic hazards for resource exploration. Thermogenic gas seeps, sea-floor gas cratering, sediment liquefaction, ice gouging, scour-depression formation, coastal and offshore storm surge and associated deposition of storm-sand, and movement of large-scale bedforms all are active sedimentary processes in this epicontinental shelf region.

Interaction between the processes of liquefaction and the formation of shallow gas pockets and craters, scour depressions, storm-sand deposits, and slumps results in sediment instability. Liquefaction of the upper 1-3 m of sediment may be caused by cyclic storm-wave loading of the Holocene coarse-grained silt and very fine-grained sand covering Norton Sound. The widespread occurrence of gas-charged sediment with small surficial craters (3-8 m in diameter and less than 1 m deep) in central Norton Sound indicates that the sea-floor sediment is periodically disrupted by escape of biogenic gas from the underlying peaty mud. During major storms, liquefaction may not only help trigger crater formation but also magnify erosional and depositional processes that create large-scale scour areas and prograde storm sand sheets in the Yukon prodelta area.

Erosional and depositional processes are most intense in the shallower parts of northern Bering Sea and along the coastline during storm surge flooding. Ice gouges are numerous and ubiquitous in the area of the Yukon prodelta, where the sediment is gouged to depths of 1 m. Though much less common than in the prodelta, ice gouges are present throughout the rest of northern Bering Sea where water depths are less than 20 m and at times where water is as much as 30 m deep. In the Yukon prodelta area and in central Norton Sound, where currents are constricted by shoal areas and flow is made turbulent by local topographic irregularities (such as ice gouges), storm-induced currents have scoured large (10- to 150-m disinter), shallow (less than 1 m deep) depressions. The many storm-sand layers in Yukon prodelta mud show that storm surge and waves have generated bottom-transport currents that deposit layers of sand as thick as 20 cm as far as 100 km from land. St Orm surge runoff may reinforce the strong geostrophic currents near Bering Strait, causing intermittent movement of even the largest sand waves (10-200 m wavelength, to 2 m height).

INTRODUCTION

Studies of potential geologic hazards on Norton Basin sea floor in northern Bering Sea have been conducted by the U.S. Geological Survey (USGS) in evaluating oil and gas lease tracts preparatory to Outer Continental Shelf (OCS) leasing. The data base for this evaluation included 9000 km of high-resolution geophysical tracklines (Nelson et al., 1978a; Thor and Nelson, 1978; Larsen et al., 1979) 1000 grab samples, 400 box cores and 60 vibracores; in addition, hundreds of camera, hydrographic, and current meter stations have been occupied during the past decade by USGS, National Oceanic and Atmospheric Administration (NOAA), and University of Washington oceanographic vessels (Figs. 1 and 2).

The northern Bering Sea is a broad, shallow epicontinental shelf region covering approximately 200,000 km^2 of subarctic sea floor between northern Alaska and the U.S.S.R. The shelf can be divided into four general morphologic areas: (1) the western part, an area of undulating, hummocky relief formed by glacial gravel and transgressive-marine sand substrate (Nelson and Hopkins, 1972); (2) the southeastern part, a relatively flat featureless plain with fine-grained transgressive-marine sand substrate (McManus, et al., 1977); (3) the northeastern part, a complex system of sand ridges and shoals with fine- to medium-grained transgressive sand substrate (Nelson, et al., 1978b); and (4) the eastern part, a broad, flat marine reentrant (Norton Sound) covered by Holocene silt and very fine sand (Nelson and Creager, 1977). A detailed discussion of bathymetry and geomorphology of northern Bering Sea is given by Hopkins and others (1976) (Fig. 3).

The northern Bering Sea is affected by a number of dynamic factors: winter sea ice, sea level setup, storm waves and strong currents (geostrophic, tidal, and storm). The sea is covered by pack ice for about half the year, from November through May. A narrow zone of shorefast ice (sea ice attached to the shore) develops around the margin of the sea during winter months. Around the front of the Yukon River Delta, shorefast Ice extends to 40 km offshore (Thor et al., 1978). During the open-water season, the sea is subject to occasional strong northerly winds, in the fall strong south-southwesterly winds cause high waves and storm surges along the entire west Alaskan coast (Fathauer, 1975). Throughout the year, there is a continual northward flow of water is present with currents intensifying on the east side of strait areas (Coachman et al., 1976). Although diurnal tidal ranges are small (less than 0.5 m), strong tidal currents are found in shoreline areas and within central Norton Sound (Fleming and Heggarty, 1966; Cacchione and Drake, 1979a).

This paper reviews basic sedimentary processes of this epicontinental shelf region and discusses certain potential geologic hazards related to these processes: thermogenic gas seepage, biogenic gas saturation of sediment and cratering, sediment liquefaction, ice gouging, current scouring, storm sand deposition, and mobile bedform movement (Fig. 4). These geologic hazards may pose problems for the future development of offshore resources in Norton Basin.

SEDIMENTARY PROCESSES

YUKON DELTA PROCESSES

The Yukon River drains an area a little less than 900,000 km^2, providing a water discharge of approximately 6000 m^3 per second and a sediment load of 70-90 million metric tons per year (Dupré and Thompson, 1979; Cacchione and Drake, 1979a). The sediment load, almost 90 % of all sediment entering the Bering Sea, is composed mainly of very fine sand and coarse silt with very little clay.

The Yukon delta plain, like many deltas described, is fringed by prograding tidal flats and distributary mouth bars. The delta front and prodelta are offset from the prograding shoreline by a broad platform (referred to as a subice platform) 30 km at its widest reach. This platform appears to be related to the presence of shorefast ice that fringes the delta for half the year. The term delta front describes the relatively steep margin of the offshore delta environment characterized by rapid deposition of sediment in water 2 to 10 m deep. The prodelta, an area of extremely gentle slopes, marks the distal edge of the deltaic sediments extending as far as 100 km offshore.

Processes on the Yukon Delta and offshore operate under seasonal regimens (Dupré and Thompson, 1979). The ice-daninated regimen begins with freeze-up in late October or November. Shorefast ice extends 10 to 40 km offshore where it is terminated by a series of pressure ridges and shear zones formed by the interaction of shorefast ice with the highly mobile seasonal pack ice.

River breakup, typically in May, marks the beginning of the river dominated regimen. Once the shorefast ice melts or drifts offshore, sedimentation is daninated by normal deltaic processes under the influence of the high discharge of the Yukon River.

Increasingly frequent southwest winds and waves associated with major storms during late summer mark the beginning of the storm-dominated regimen. High wave energy and decreasing sediment discharge fran the Yukon cause considerable coastal erosion and reworking of deltaic deposits.

COASTAL STORM SURGE

In November 1974, a severe storm moved from southwest to northeast across the Bering Sea. Peak winds were 111 km per hour fran the south, and nearshore waves were reported to be 3 to 4 m in height (Fathauer; 1975). Coastal flooding extended from Kotzebue Sound (north of Bering Strait) to just north of the Aleutian Islands (Fathauer, 1975). The maximum sea level setup, measured by the elevation of debris lines along the coast of Norton Sound, ranged from 3 to 5 m above mean sea level (Sallenger et al., 1978). During this storm, extensive inland flooding occurred and erosion of 2 to 5 m high coastal bluffs took place near Nome. Irregular landward erosion, as much as 18 m, occurred west of Nome, where bluffs are 3 to 5 m high. East of Nome, where bluffs are 1.5 to 2 m high, landward erosion was as much as 45 m. Water level in the Norton Sound area reached its peak on 12 November, when as much as 2 m of water was standing in the village of Unalakleet and the static high-water line at Nome was 4 m above mean low low-water.

STORM CURRENTS

The transport of sediment in Norton Sound and Norton Basin can be described in terms of distinct quiescent and storm regimes (Cacchione and Drake, 1979a). The quiescent regime is characterized by generally low levels of sediment transport caused mainly by tidal currents. Fine silt and clay move as "wash load," and bedload transport is negligible except in shallow areas where surface waves become dominant. Current speeds in this regime are no greater than 30 cm/sec.

Although calm-weather conditions prevail for about 90% of the year in the northern Bering Sea, less than 50% of the sediment transport takes place under these conditions (Cacchione and Drake, 1979a). Norton Sound is commonly exposed to strong southerly and southwesterly winds generated by low-pressure weather systems in September, October and November. A two-day storm in September 1977 transported sediment equal to the transport that would occur during four months of quiescent conditions. Current speeds were as much as 70 cm/sec during this storm.

Graded storm-sand layers, to 20 cm thick (Nelson, 1977), occur in sea-floor strata of the northern Bering Sea, widespread evidence of major storm-surge events. The effects of storm surge are intensified by two factors: 1) extremely shallow water depth (less than 20 m), and 2) strong bottom return currents that may move large amounts of sediment northward to the Chukchi Sea. The thickness of Holocene sediment in Norton Sound, relative to Holocene sediment input from the Yukon River indicates that significant amounts of sediment have been resuspended and transported out of Norton Sound (Nelson and Creager, 1977). About 10% of the Yukon River input into Norton Sound may be carried as suspended sediment through the Bering Strait into the Chukchi Sea under nonstorm conditions (Cacchione and Drake, 1979a) . As much as 40% of Holocene sediment discharged from the Yukon River appears to be missing from Norton Sound. This difference of 30% may be material that has been resuspended and transported during storms (Cacchione and Drake 1979a).

Storm currents not only resuspend and transport massive amounts of suspended sediment, but also appear to move large amounts of sand in bedload transport for considerable distances offshore. Graded storm-sand layers are extensive throughout southern Norton Sound; their thickening toward the Yukon subdelta, the apparent source region, suggests massive movement of bedload sediment away from the delta toward the adjacent offshore region during storms (Nelson, 1977).

WAVE EFFECTS

Waves and wave-induced currents are the dominant sedimentological agents on the inner shelf of northwestern Norton Sound and in the approaches to Bering Strait (Hunter and Thor, 1979). Sedimentary features common to both areas include sand and gravel patches and ribbons, wave ripples, sand waves, and ice gouges (Hunter and Thor, 1979).

Wave ripples with spacings to 2 m are common in both the Port Clarence and Nome areas in zones where sediment is well sorted and grain size ranges from coarse sand to pebbly gravel. Ripples in the Port Clarence area trend northwest-southeast and can be explained as the result of storm waves from the southwest Bering Sea. Trends of ripples in the Nome area indicate dominant wave activity from south to southwest.

Ribbons of sand and gravel are well developed near the entrance to Port Clarence. These bedforms may be produced by wave action or by wave--induced net water motion in the direction of wave propagation.

A rich assemblage of depositional and erosional features, both wave-formed and current-formed, occupy the floor in shallow water close to the southern shore of Seward Peninsula. Wave-formed features are more common; some of the current-formed features imply considerable sediment transport by strong bottom tidal currents.

Only the broad patterns of wave and current movement in southwestern Norton Sound are known. The major wave trains originate in the southern Bering Sea: waves move northward and refract clockwise around protruding Yukon shoals. Smaller waves with shorter periods are generated by northeasterly winds and move southwestward.

LIQUEFACTION

The Yukon River sediment that covers most of the bottom of Norton Sound (McManus et al., 1977) is primarily silt with considerable amounts of very fine sand in some areas and a generally minor content of clay-size material. The sediment thickness is generally less than 3 m, except near the Yukon Delta, where accumulations are as thick as 10 m (Olsen et al., 1979). The material is generally dense; there are zones of relatively loose sediment (material of low density) in gas-charged areas. In the delta areas sampled by

6-m vibracores, relatively loose zones of sediment were observed above and between dense layers.

Fresh-water peaty mud beneath Yukon marine silt is somewhat over-consolidated and contains substantial amounts of organic carbon and gas. The presence of gas indicates that the pore pressures in the peaty muds may be high. If it is, the strength of the material could be low despite its highly consolidated state.

The dominantly coarse-silt to fine-sand-size texture of the material, occurrence of loose sediment zones, and theoretical calculations utilizing GEOPROBE cyclic wave loading data (Olsen et al., 1979; Clukey et al., 1980) indicate that Yukon prodelta sediment in southwestern Norton Sound is susceptible to liquefaction. Potential liquefaction of the prodelta deposits is attributable to cyclic loading resulting from exposure of the Yukon prodelta to large storm waves from the southwest. Water depths are sufficiently shallow that much of the wave generated surface energy is imparted to the bottom sediment, possibly resulting in liquefaction of the upper 1-2 m of sediment cluing extreme storm surge events (Clukey et al., 1980). This liquefaction potential of prodelta sediment influences storm-sand transport, formation of sediment depressions, and gas cratering.

ICE SCOUR

Ice on the Bering shelf scours and gouges surficial sediment of the sea floor (Fig. 5). The annual ice cover in this subarctic setting is generally thin (less than 2 m); thick ice capable of gouging forms where pack ice collides with and piles up against stationary shorefast ice developing numerous pressure ridges (Thor and Nelson, this volume) . A wide well-developed shear zone forms in southwest Norton Sound as ice moving southward from the northeast Bering Sea and westward along southern Norton Sound converges in the shallow water of the Yukon prodelta. Consequently, numerous zones of pressure ridges are formed. This region at 10- to 20-m water depth has the maximum ice-gouge density. Gouges are found in water to 30 m deep, and furrows are as much as 1 m deep. Ice-gouging affects the sea floor under shorefast areas only minimally, or not at all (Thor and Nelson, 1980).

CURRENT SCOUR DEPRESSIONS

Zones of large flat-floored depressions in Norton Sound occur mainly in two areas: west of the Yukon prodelta and 50 km southeast of Nome, on the flank of a broad shallow trough (Fig. 6) (Larsen et al., 1979). These features range fran individual more or less elliptical depressions 10 to 30 m in diameter to large areas with irregular margins, 80 to 150 m in diameter. The depressions are 60 to 80 cm deep (Larsen et al., 1980).

Bottom current speeds in depression areas are 20 to 30 cm per second under nonstorm conditions and were measured at 70 cm per second during a typical autumn storm (Cacchione and Drake, 1979a). Both zones of depressions are on flanks of gently sloping shoals, where strong tidal or geostrophic currents shear against the slopes. Small-scale ripple bedforms are associated with depression areas and mean grain size ranges from 4 phi to 4.5 phi (0.063 mm to 0.044 mm). Depressions in the Yukon delta area are associated with extensive ice gouging. The gouge furrows commonly expand into large shallow depressions (Larsen et al., 1979 and Thor and Nelson, this volume).

Experiments in flumes containing fine sand and silt have shown that currents flowing over an obstruction will scour material immediately downcurrent from the obstruction (Young and Southard, 1978). The large scour depressions observed in Norton Sound may be a characteristic erosional bedform developed during storms when strong currents and high wave energy are focused on silt-covered slopes where local topographic disruptions set off flow separation and downcurrent scour.

SANDWAVE DYNAMICS

Strong geostrophic currents prevail throughout much of the northern Bering Sea, particularly where westward land projections interject into the northward flow, as in the eastern Bering Strait area (Flemming and Heggarty, 1966; Coachman et al., 1976). In such regions large bedforms develop and migrate, forming an unstable sea floor (Nelson et al. , 1978b) . These large bedforms include large-scale sand waves 1 to 2 m high with wavelengths to 200 m, and small-scale sand waves 0.5-1 m high with wavelengths of 10 m. They occupy the crests and some flanks of a series of linear sand ridges 2 to 5 kin wide and as much as 20 km long between Port Clarence and King Island.

Sand wave movement and bedload transport take place during calm weather (Nelson et al., 1978b) , but maximum change apparently occurs when severe southwesterly storms generate sea level set-up in the eastern Bering Sea that enhances northerly currents. In contrast, strong north winds from the Arctic reduce the strength of the northerly currents and thereby arrest bedform migration.

SEDIMENT GAS CHARGING

The distribution of acoustic anomalies suggests that almost 7000 km^2 of sea floor in Norton Sound and Chirikov Basin is underlain by sediment containing gas sufficient (biogenic and/or thermogenic) to affect sound transmission through these zones (Holmes, 1979a). Core-penetration rates (Nelson et al., 1978c and Kvenvolden et al., 1979a) and sediment samples from 2- to 6-m vibracores confirm gas saturation of near-surface sediment at several locations characterized by acoustic anomalies. The isotopic compositions of methane at four of the sites range from -69 to -80°/oo ($\delta^{13}C_{PDB}$) (Kvenvolden et al., 1978, 1979b). This range of values clearly indicates that the methane is formed by microbial processes, possibly operating on near-surface Pleistocene peat deposits that underlie Holocene deposits throughout the northern Bering Sea.

At one site in Norton Sound, near-surface sediment is apparently charged with CO_2 actively seeping from the sea floor accompanied by less than one percent hydrocarbon gases (Kvenvolden et al., 1979a). Methane in this gas mixture has an isotopic composition of -36°/oo, a value suggesting that it is derived mainly from thermal processes, probably operating at depth in Norton Basin (Kvenvolden et al., 1979a). Geophysical evidence indicates that the hydrocarbon gases migrate into the near-surface sediments along a fault zone (Nelson et al., 1978c). Subbottom reflector terminations on continuous seismic profiles near the fault zone outline a large zone of anomalous acoustic responses about 9 km in diameter and at a 100-m depth caused by a thick subsurface accumulation of gas. Gas geochemistry and extensive voids due to gas expansion in vibracores suggest a high degree of gas saturation at the seep site (Kvenvolden et al., 1979b) .

BIOGENIC GAS CRATERING

Small circular pits on the sea floor are found over a 20,000-km^2 area of central and eastern Norton Sound (Fig. 7). The craters in the northern Bering Sea are young features, as shown by their presence within modern ice-gouge grooves and by the fact that relict buried craters have not been observed in seismic profiles (Nelson et al., 1979b). These craters range from 1 to 10 m in diameter, averaging 2 m, and are probably less than 0.5 m deep. They are associated with numerous acoustic anomalies observed on seismic profiles and with subsurface Pleistocene peaty mud that commonly is saturated with biogenic methane (Holmes 1979b; Kvenvolden, 1979c; Nelson et al., 1979). The extensive reflector-termination anomalies and peat with a high gas content in east-central Norton Sound suggest that gas-charged sediment may be the cause of crater formation.

Two basic mechanisms for gas venting can be proposed. The first is that continuous local degassing may maintain craters as active gas vents on the sea floor. The second and more likely mechanism is that gas is intermittently vented, particularly during severe storms when near-surface sediment may liquefy.

The occurrence of surface craters in overlying marine sediment and the presence of high quantities of methane trapped beneath cohesive marine mud in Norton Sound suggest that gas venting may be episodic in this lithologic setting. Absence of craters in the noncohesive near-surface fine to medium sand and gravel of Chirikov Basin indicates that gas probably diffuses gradually through this more porous sediment that overlies the peaty mud there. Further evidence for intermittent venting of gas is the broad, shallow shape of the craters, unlike the deep, conical, actively bubbling vents of the thermogenic seep. Lack of methane in bottom water also suggests that the craters are not continually active vents.

POTENTIAL GEOLOGIC HAZARDS

THERMOGENIC GAS CAP

The extent of active gas seepage into the water column and gas saturation in near-surface sediment above a thick sediment section with acoustic anomalies suggests a possible hazard for future drilling activity in the thermogenic gas seep area south of Nome. Artificial structures penetrating the large gas accumulation at 100 m or intersecting associated faults that cut the gas-charged sediment may provide direct avenues for uncontrolled gas migration to the sea floor.

SHALLOW GAS POCKETS

Gas-charged sediment creates potentially unstable surficial-sediment conditions in Norton Sound. Approximately 7,000 km^2 of Norton Sound is underlain by acoustic anomalies with potential shallow gas pockets everywhere except under the Yukon prodelta (Holmes, 1979a; Nelson et al., 1979a). Pipelines built across areas of these potential gas pockets may be damaged by stress induced from the unequal bearing strength of gas-charged and normal sediment, particular if the near-surface sediment is undergoing liquefaction caused by cyclic loading of storm waves. The gas saturation and lateral and subsurface extent of any shallow gas pockets will have to be detailed in any site investigations for platforms or pipelines.

GAS CRATERS

Gas craters cover a large area of north-central Norton Sound. During nonstorm conditions, near-surface gas in this area may be trapped by a 1- to 2-m thick layer of impermeable Holocene mud. We postulate that the gas escapes during periodic storms forming craters at the surface. The storm processes initiate rapid changes in pore-water pressures because of sea-level setup, seiches, erosional unloading of covering mud, and possible sediment liquefaction from cyclic wave loading (Clukey et al., 1980). Gas venting and sediment craters or depressions, which seem to form during peak storm periods, may be a potential hazard to offshore facilities because of rapid lateral changes in bearing strengths and sediment collapse that forms the craters. Sediment collapse may also expose pipelines to ice gouging hazards. During nonstorm conditions, the upper several meters of sediment at many locations has reduced shear strength because of the near-surface gas saturation and presence of peat layers. Siting of artificial structures will require extensive local testing of the substrate to determine the extent and activity of gas cratering at a given site.

LIQUEFACTION

The assessment and prediction of sea-floor stability is affected by the potential of a sedimentary deposit to liquefy under cyclic loading and behave as a viscous fluid. The liquefaction potential of Norton Sound sediment is great in central Norton Sound and in the vicinity of the western Yukon prodelta (Clukey et al., 1980; Olsen et al., 1979). Possible causes of liquefaction include upward migration of gas from thermogenic and biogenic sources, earthquakes, and ocean waves. Bottom features that may be caused in part by liquefaction include scour depressions and abundant sediment cratering where Yukon sediment is thin.

Loss of substrate support by sediment liquefaction is a problem that must be faced in the construction of pipelines, drilling platforms, and other types of structures resting on the sea floor. Full assessment of this problem requires extensive studies of in situ pore pressure, gas saturation, and wave cyclic loading during storms.

ICE SCOUR

The maximum intensity of ice-gouging occurs in central Norton Sound at 10- to 15-m depths in an area surrounding the Yukon Delta. The remaining area of Norton Sound, where depths are less than 10 m or more than 20 m, has a low density of gouging, or none at all. Special studies of nearshore areas off Nome and Port Clarence were made when they became potential centers for commercial development and activity. Offshore Nome, the focal point for logistics in the northern Bering Sea because it is an area of ice divergence, only a few gouges were found in water more than 8 m deep (Thor and Nelson, this volume). Several gouges were found at the northern end of Port Clarence spit and inside the tidal inlet, but again none occurred in water less than 8 m deep.

Ice gouging presents some design problems and potential hazards to installations in or on the sea floor. Pipelines and cables should be buried at a depth that allows for maximum ice gouging of 1 m, plus a safety factor for combined effects with current scour around the western Yukon prodelta front or gas cratering in central Norton Sound.

CURRENT SCOUR DEPRESSIONS

The highest density of scour depressions in Norton Sound is in two areas: (1) west and northwest of the Yukon delta and (2) southeast of Nome (Fig. 6). In areas of high density, artificial structures that disrupt current flow may cause extensive erosion of Yukon-derived silt or very fine-grained sand and create potentially hazardous undercutting of the structures. Even buried structures such as pipelines may be subject to scour because strong currents can greatly broaden and deepen naturally occurring ice gouges, thus exposing the structures. The severity of scour depressions is greatest where they occur with ice-gouging in the Yukon delta areas. Replicate surveys have shown that scour depressions recur annually. Full assessment of this geologic hazard requires long-term current monitoring in specific localities of scour to predict current intensity and periodicity, especially during severe storms, when measured current speeds have increased more than 100% under moderate storm conditions (Cacchione and Drake, 1979b).

MOBILE BEDFORMS

Large migrating bedforms form an unstable sea floor in the area west of Port Clarence. Actual rates of bedform movement are not known, but development and decay of sand waves up to 2 m in height has been observed during a one-year period. Pipelines could be subject to damaging stress if free spans developed where the structure crossed such areas of migrating 2-m high sand waves.

Studies made to this time indicate that potential for the most extreme scour exists in regions of sand ribbons and gravel plus shell pavement within the strait. Sea floor relief changes most rapidly in the Port Clarence sand-wave area, where the scour in sand-wave troughs may reach depths of 2 m. Replicate surveys have shown that such scour may occur each year in some areas of the Port Clarence sand wave field. Long-term monitoring of currents and bedform movement is particularly important in determining actual rates of change in this area, the only large natural harbor on the Alaskan coast north of the Aleutians.

COASTAL AND OFFSHORE STORM SURGE HAZARDS

The northern Bering Sea has a known history of major storm surges accompanied by widespread changes in sea-floor sedimentation (Cacchione and Drake, 1979a; Fathauer, 1975; Nelson, 1977); these changes complicate maintenance of sea-floor installations and mass transport of pollutants. The November 1974 storm is the most intense measured in historic time; storms of 1913 and 1946 caused considerable damage (Fathauer, 1975). Severe storms, such as the November 1974 storm, have caused extensive flooding along the Norton Sound coast between Nome and Unalakleet and on the St. Lawrence Island coast (Sallenger et al., 1978). At Nome, storm surge and waves overtopped a sea wall, causing damage reported at nearly 15 million dollars (Fathauer, 1975). Storm surge periodicity and intensity will have to be carefully studied in planning where and whether pipelines should come ashore in this area.

Rapid sedimentation of thick storm sand layers (15-20 cm) is a problem in the Yukon delta area. Pipelines, offshore facilities, and other structures impeding the erosion, transport, and redeposition of sediment in southern Norton Sound will require careful design. Accurate monitoring of the storm surge process will require long-term deployment of an array of current meters and tide gauges in the northern Bering sea.

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Figure Captions

Figure 1. Sampling station locations for U.S. Geological Survey research in northern Bering Sea between 1967 and 1978.

Figure 1a. Cross-hatched area of Figure 1, showing closely spaced sampling grid offshore Nome.

Figure 2. Geophysical trackline surveys for U.S. Geological Survey research in northern Bering Sea 1967-1978.

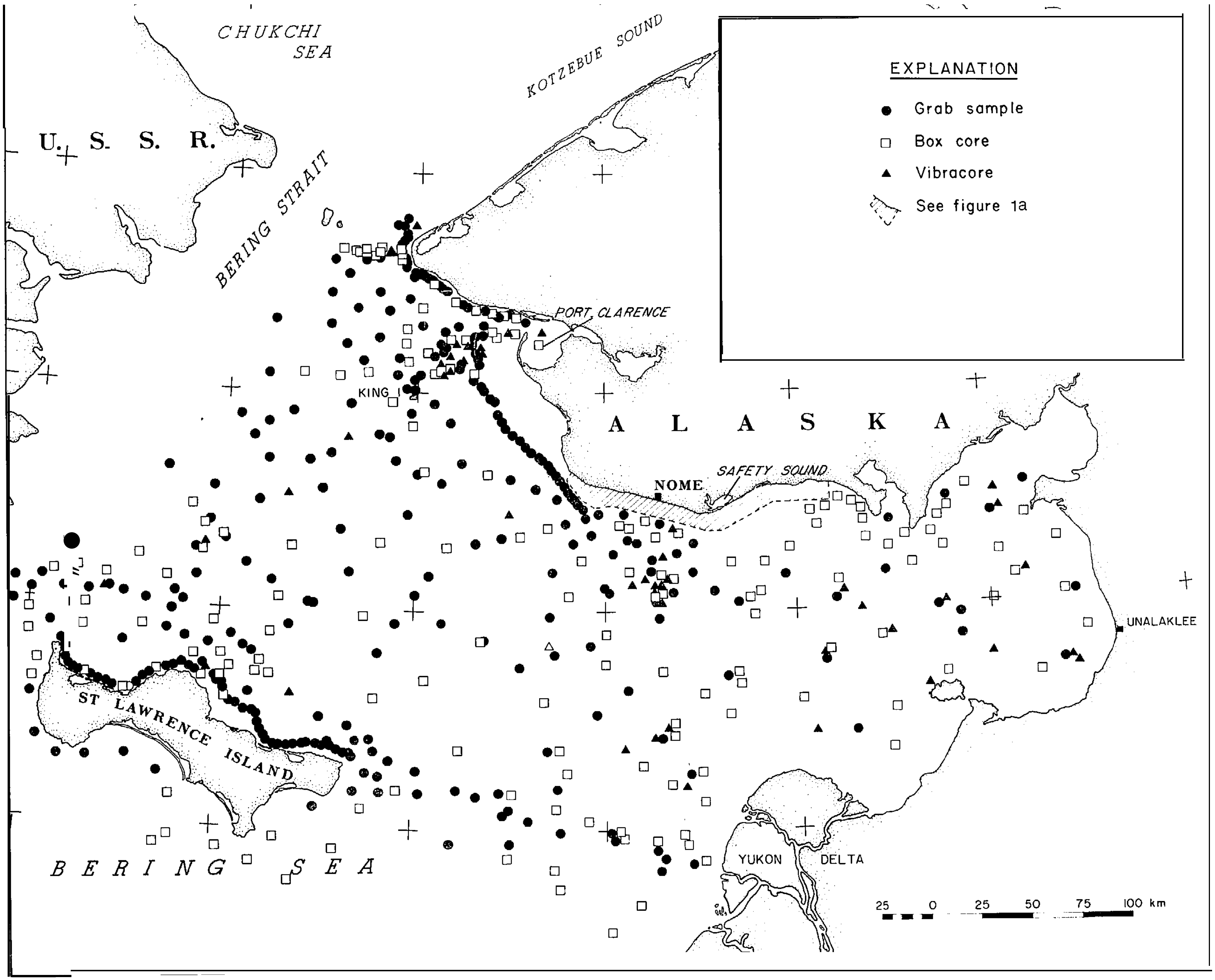
Figure 3. Generalized bathymetry of northern Bering Sea in 10-m contour intervals.

Figure 4, Potentially hazardous areas of northern Bering Sea (from Thor and Nelson, 1979).

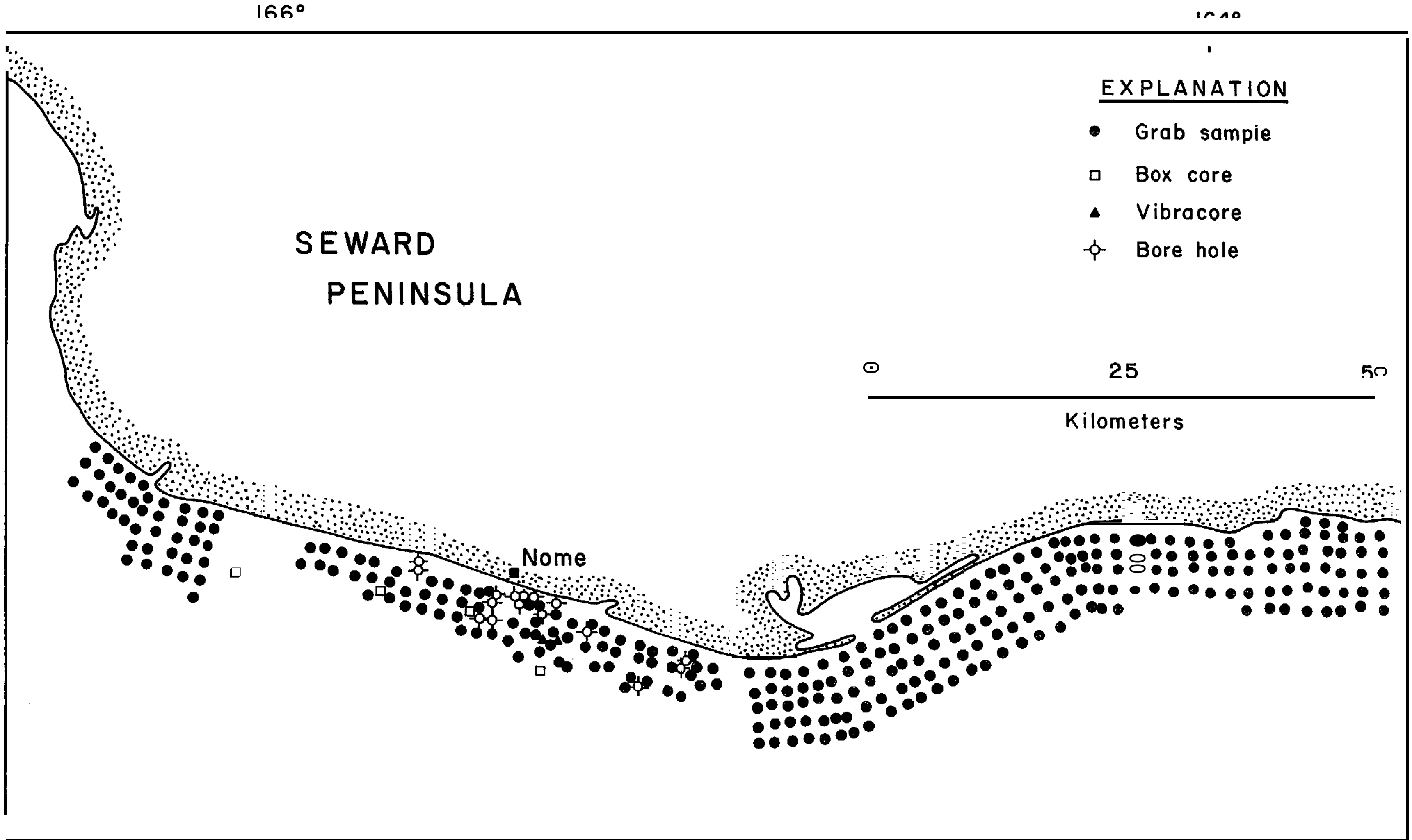
Figure 5. Distribution and density of ice gouging, direction of mwement pack ice, and limits of shorefast ice in northern Bering Sea (from Thor and Nelson, 1979).

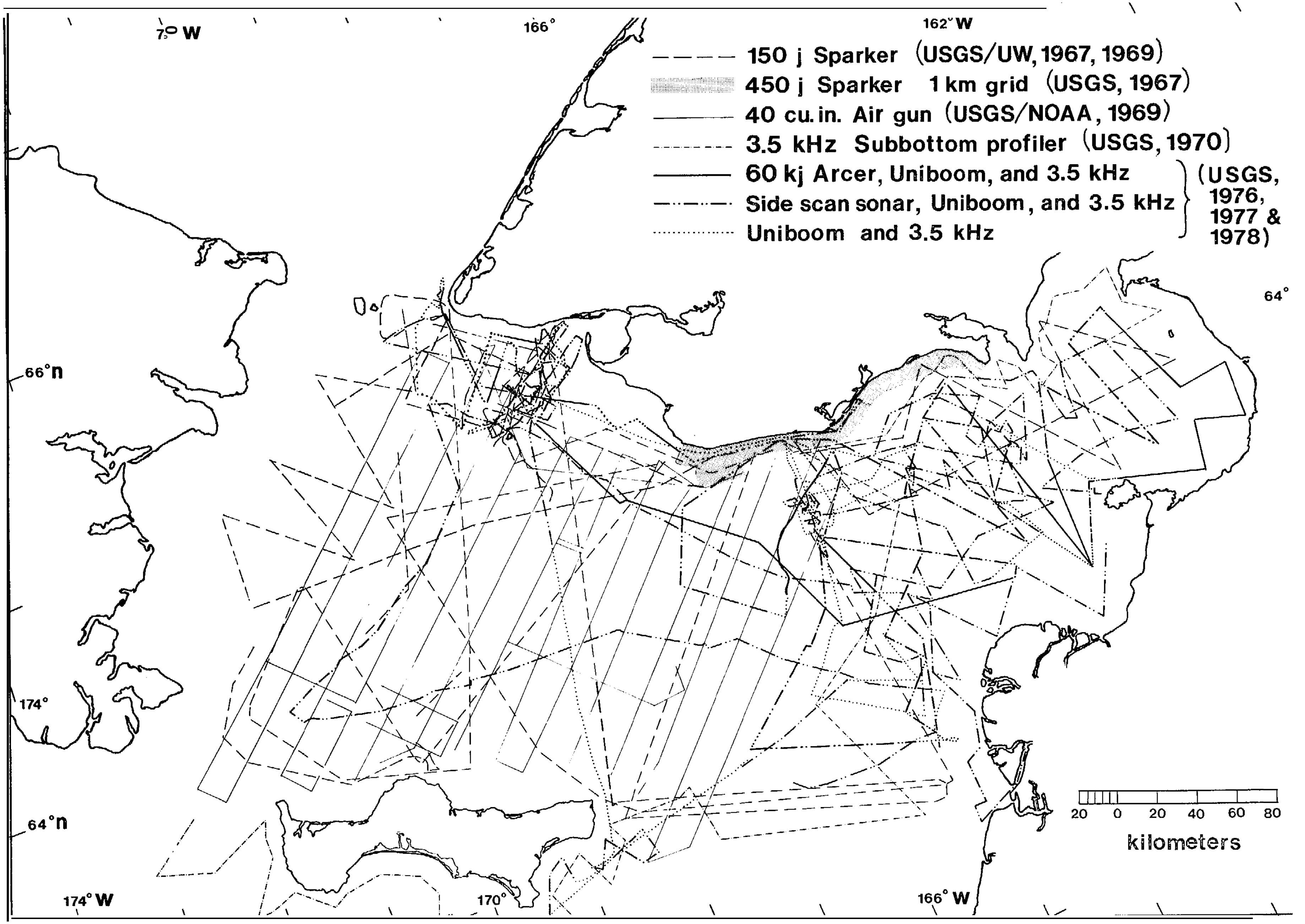
Figure 6. Location of scour depressions? extensive scour and ripple zones, and strong bottom currents in Norton Sound, showing area of storm sand deposition (modified from Larsen et al., 1980).

Figure 7. Distribution and density of craters on sea floor of Norton Sound, showing isopachs of Holocene mud derived from the Yukon River and deposited since Holocene postglacial sea-level rise (from Thor and Nelson, 1979).

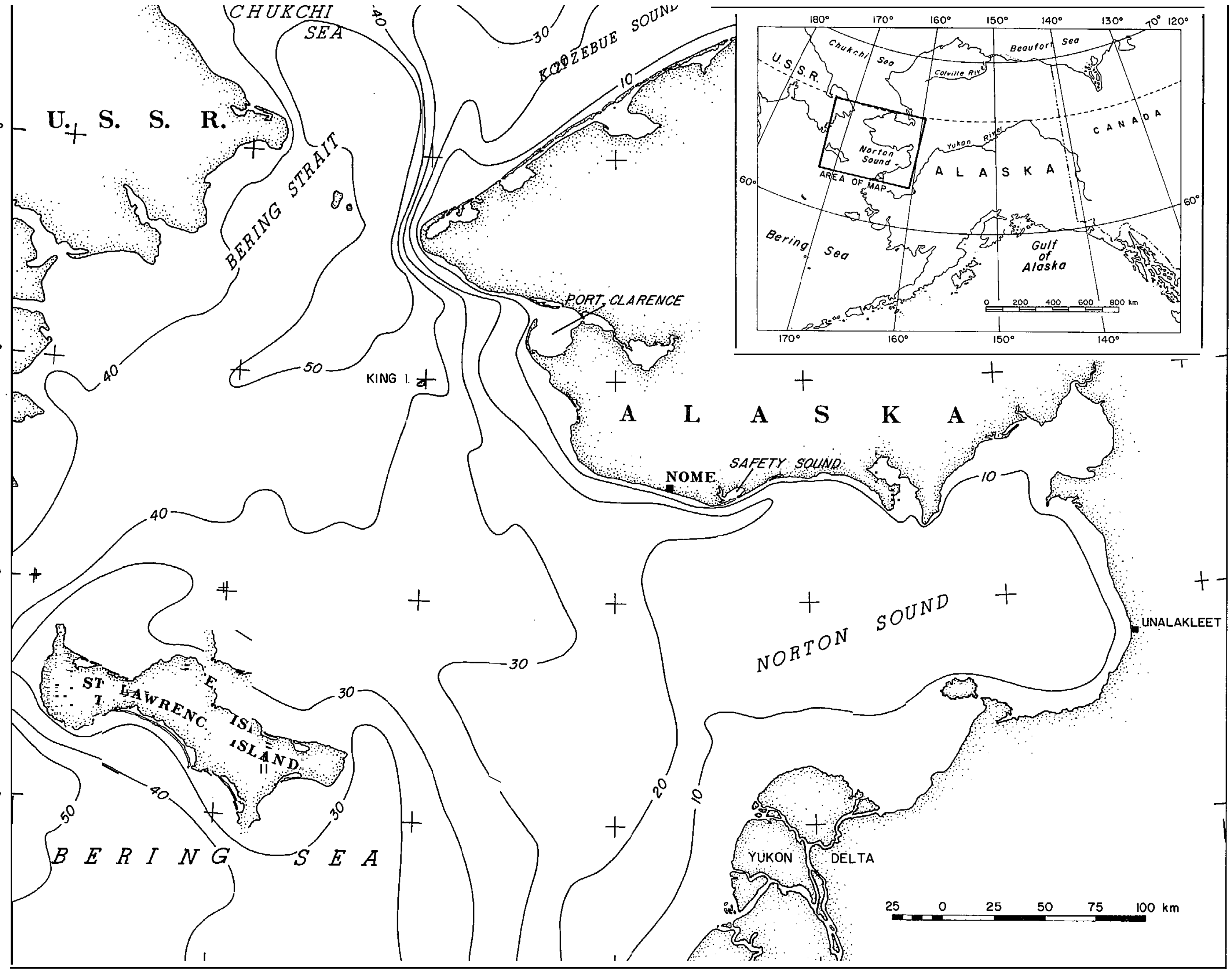


CHUKCHI SEA
KOTZEBUE SOUND
U. S. S. R.
BERING STRAIT
PORT CLARENCE
KING I
A L A S K A
NOME
SAFETY SOUND
UNALAKLEE
ST LAWRENCE ISLAND
YUKON DELTA
BERING SEA
66°
65°
64°
63°
EXPLANATION
Grab sample
Box core
Vibracore
See figure 1a
25 0 25 50 75 100 km

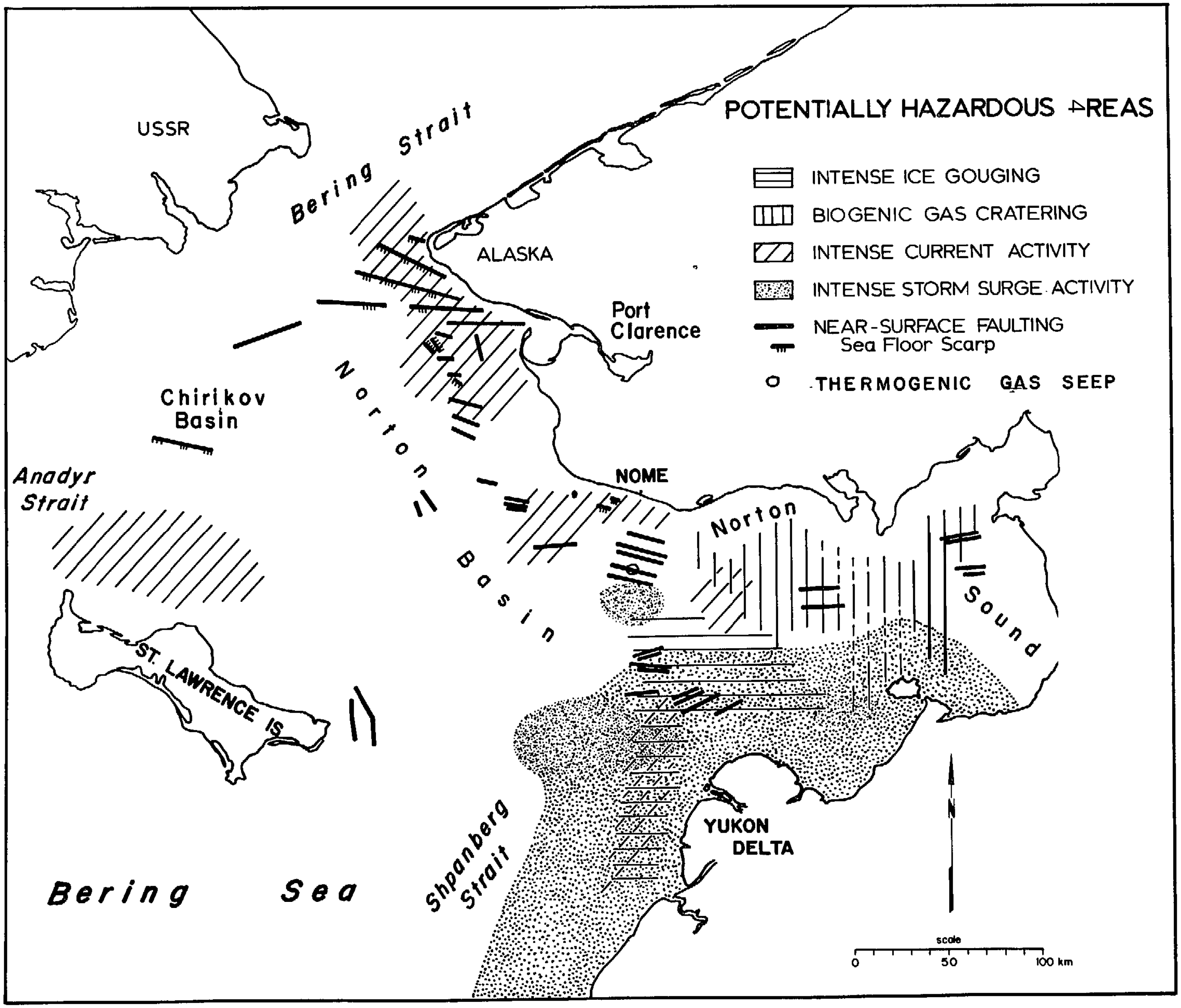

166°
164°
EXPLANATION
Grab sample
Box core
Vibracore
Bore hole
SEWARD
PENINSULA
0
25
50
Kilometers
Nome

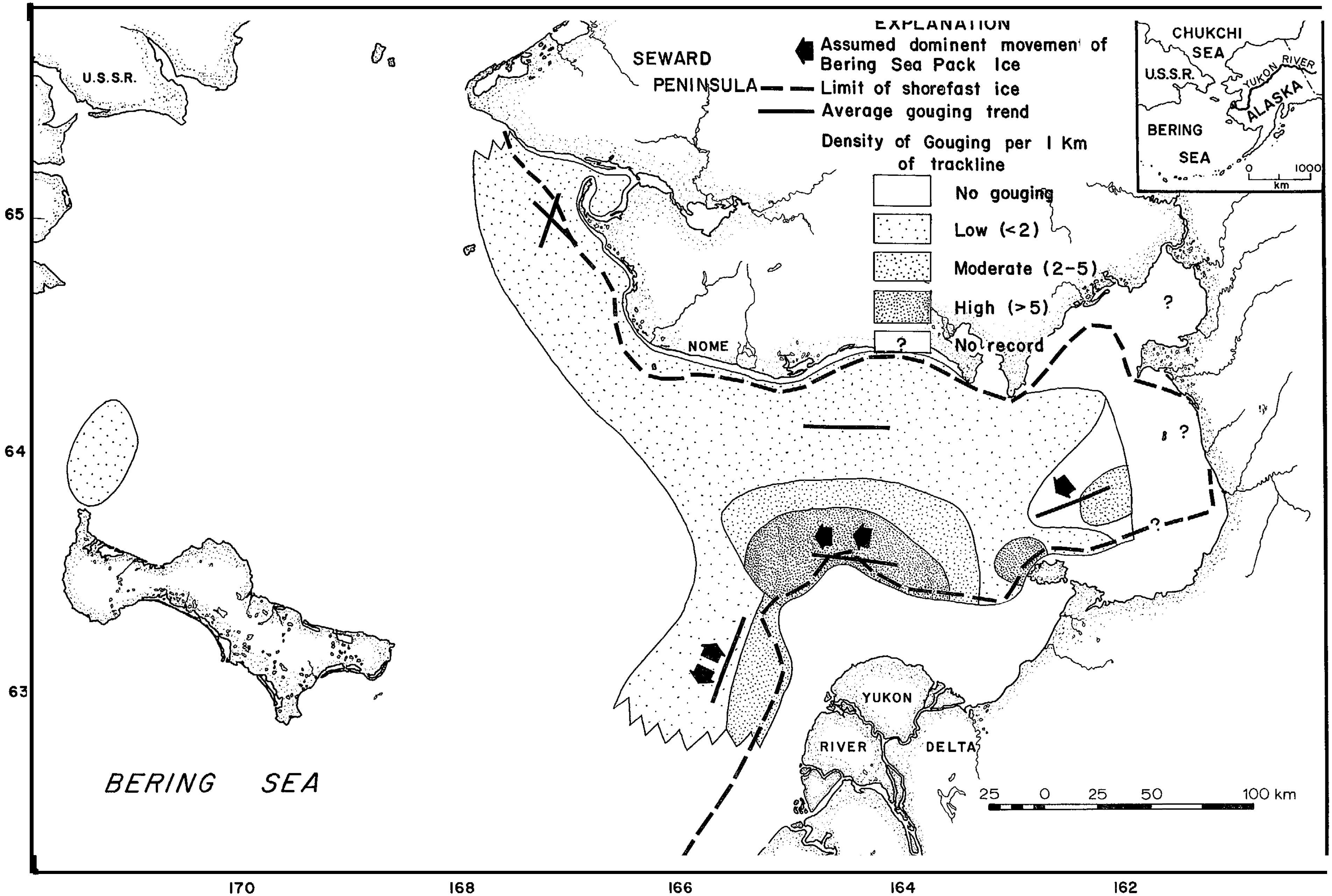


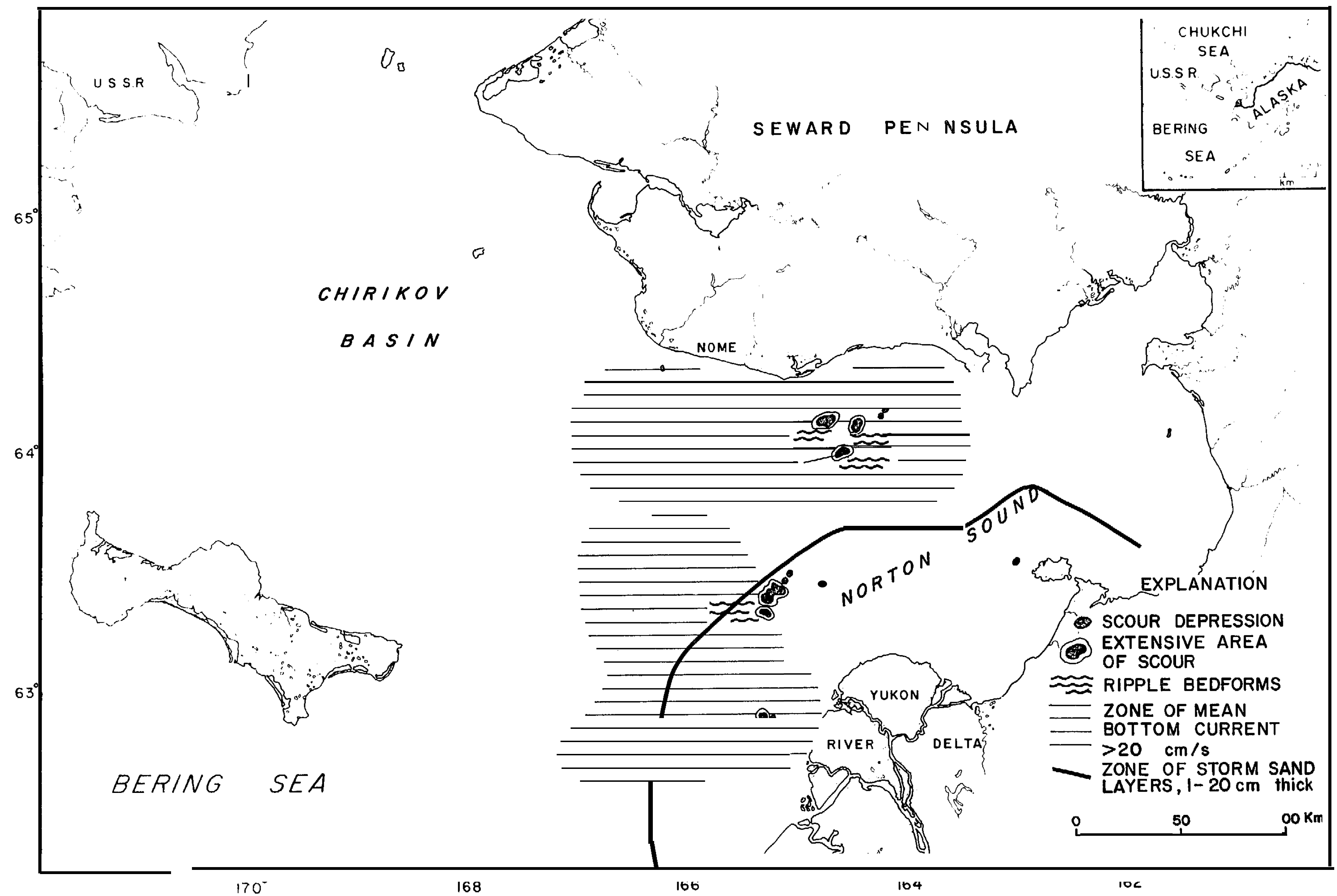
150 j Sparker (USGS/UW, 1967, 1969)
450 j Sparker 1 km grid (USGS, 1967)
40 cu. in. Air gun (USGS/NOAA, 1969)
3.5 kHz Subbottom profiler (USGS, 1970)
60 kj Arcer, Uniboom, and 3.5 kHz
Side scan sonar, Uniboom, and 3.5 kHz
Uniboom and 3.5 kHz
(USGS, 1976, 1977 & 1978)
162° W
166°
64°
66° n
174°
64° n
174° W
170°
166° W
20 0 20 40 60 80
kilometers



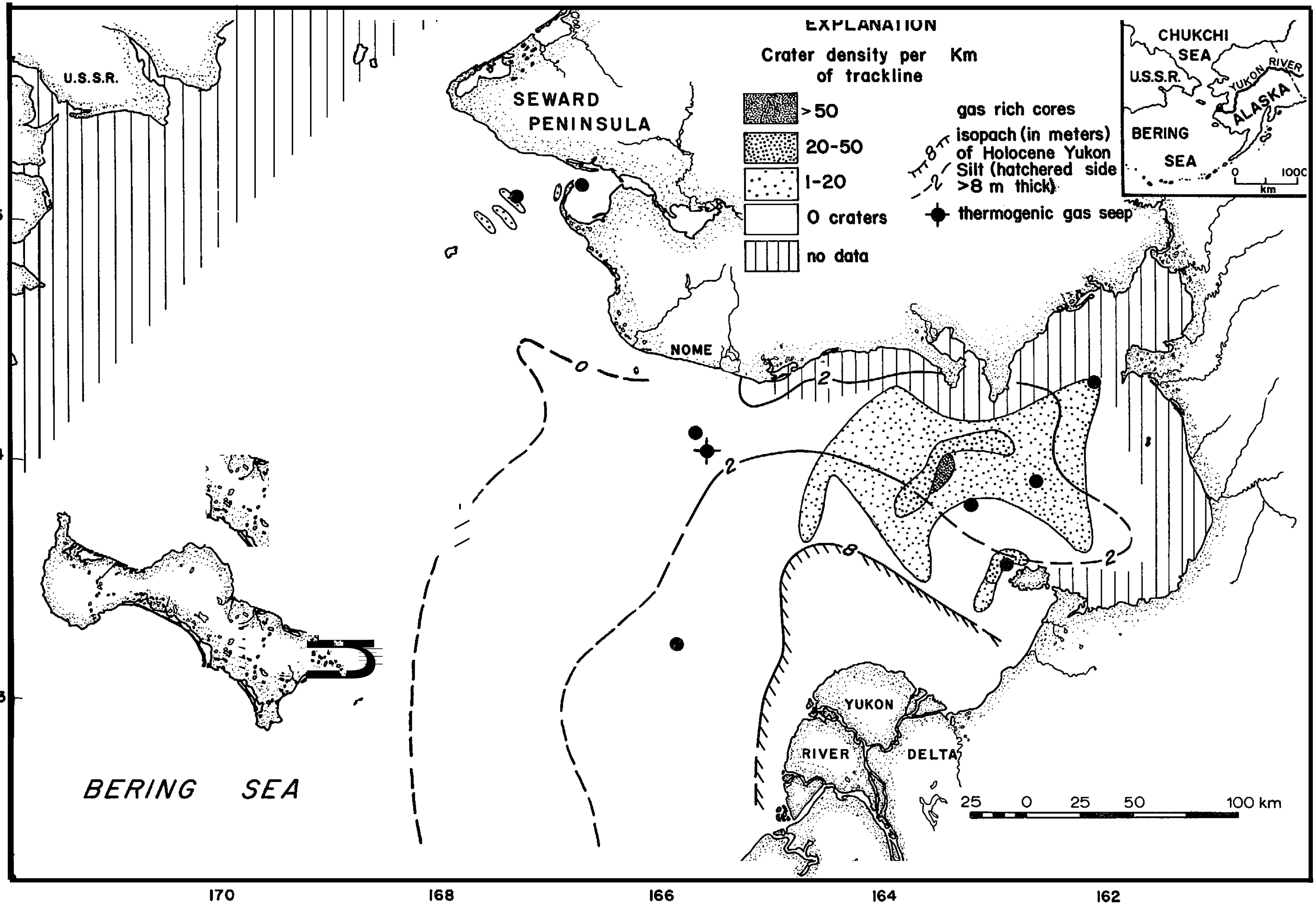
U. S. S. R.
CHUKCHI SEA
KOTZEBUE SOUND
BERING STRAIT
KING I.
PORT CLARENCE
ALASKA
NOME
SAFETY SOUND
NORTON SOUND
UNALAKLEET
ST. LAWRENCE ISLAND
YUKON DELTA
BERING SEA
66°
65°
64°
63°
25 0 25 50 75 100 km
Chukchi Sea
Beaufort Sea
Colville River
Yukon River
CANADA
ALASKA
Norton Sound
AREA OF MAP
Bering Sea
Gulf of Alaska
0 200 400 600 800 km


POTENTIALLY HAZARDOUS AREAS
INTENSE ICE GOUGING
BIOGENIC GAS CRATERING
INTENSE CURRENT ACTIVITY
INTENSE STORM SURGE ACTIVITY
NEAR-SURFACE FAULTING
Sea Floor Scarp
THERMOGENIC GAS SEEP
USSR
Bering Strait
ALASKA
Port Clarence
Chirikov Basin
Norton Basin
NOME
Norton Sound
Anadyr Strait
ST. LAWRENCE IS.
YUKON DELTA
Shpanberg Strait
Bering Sea
N
scale
0
50
100 km


EXPLANATION
Assumed dominent movement of Bering Sea Pack Ice
Limit of shorefast ice
Average gouging trend
Density of Gouging per 1 Km of trackline
No gouging
Low (<2)
Moderate (2-5)
High (>5)
No record
SEWARD PENINSULA
NOME
U.S.S.R.
BERING SEA
YUKON RIVER DELTA
CHUKCHI SEA
YUKON RIVER
ALASKA
0 1000 km
25 0 25 50 100 km
65
64
63
170
168
166
164
162



CHUKCHI SEA
U.S.S.R
ALASKA
BERING SEA
km
U S S.R
SEWARD PEN NSULA
CHIRIKOV BASIN
NOME
NORTON SOUND
YUKON RIVER DELTA
BERING SEA
EXPLANATION
SCOUR DEPRESSION
EXTENSIVE AREA OF SCOUR
RIPPLE BEDFORMS
ZONE OF MEAN BOTTOM CURRENT >20 cm/s
ZONE OF STORM SAND LAYERS, 1-20 cm thick
0
50
00 Km
65°
64°
63°
170°
168
166
164


EXPLANATION
Crater density per Km of trackline
>50
20-50
1-20
0 craters
no data
gas rich cores
isopach (in meters) of Holocene Yukon Silt (hatchered side >8 m thick)
thermogenic gas seep
CHUKCHI SEA
U.S.S.R.
YUKON RIVER
ALASKA
BERING SEA
0 1000 km
U.S.S.R.
SEWARD PENINSULA
NOME
YUKON RIVER DELTA
BERING SEA
25 0 25 50 100 km
0
2
8
65
64
63
170
168
166
164
162